CHANGES OF THE VISTULA RIVER CHANNEL AND FLOODPLAIN IN THE LAST 200 YEARS

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Abstract: The Vistula River is a typical Central-European river flowing from the mountains across basins and upland belts to the lowlands. The Vistula valley is modelled by a river with a complex hydrological regime. In its upper reaches, floods driven by summer rainfall prevail, while in the lower reaches snowmelt floods are important. Deforestation favoured a natural propensity for river braiding. In the mid-19th century, the channelization of the upper Vistula (in the Carpathian foreland) and the lower reaches was commenced with, while the middle streach was left in a natural state, such that the river has in places preserved a braided pattern up to the present day. The channelization followed by construction of reservoirs caused downcutting and aggradation to occur, such that opposing tendencies were observed in particular reaches of the river channel. In addition, flood embankments confined aggradation to the intra-embankment area. Thus, the functioning of the Vistula River system is largely controlled by diverse human activity. Unconstrained flow and river load transport along the whole river length are only partly possible during extreme floods. The present-day adjustment tendencies also relate to ongoing changes in land-use in the drainage basin, as well as on global climatic changes.

Key words: Vistula River, channelization/regulation, present-day changes of floodplain, downcutting, aggradation.

INTRODUCTION

The Vistula River is one of the great central European rivers, flowing from the mountains in the South (the Alps, Sudetes, Carpathians) towards the North or Baltic Seas. All these rivers traverse a series of morphological units, starting from the mountain headwaters and submontane basins, crossing an upland belt and, then, entering an extensive lowland zone which, in the eastern part, was several times occupied by the Scandinavian ice sheet. In the catchments of the Elbe, Oder and Vistula rivers, we find the remains of former streamways, later crossed by rivers flowing straight to the sea. Another characteristic feature of this zone is a gradual change of hydrological regime from one dominated by rainy floods in the West to one with more pronounced snowmelt floods towards the East. Therefore, in their upper reaches especially, the river floods are driven by heavy summer rainfall.

The evolution of the Vistula River valley in the last 10–15,000 years has been studied in detail under IGCP Project 158, which focused on the palaeohydrology of the temperate zone (Starkel *et al.* 1991), as well as on the role of human impact in the last few millennia. It was the largest catchment and the longest river studied within this Project. The results were published in six volumes (Starkel, ed. 1982–1996).

This paper tends to continue those studies but concentrates on the processes of and trends to the evolution of the Vistula river channel and floodplain. Its aim is to characterize these during the last 100–200 years of direct human impact, by focusing on the metachronous regulation of the river course and the transformation of water discharge and the sediment load. It therefore supplements previous studies. Specifically, this paper results from multi-specialist cooperation of geographers, namely a geomorphologist concentrating on the role of humans in long-term trends (L. Starkel), a hydrologist working on the Vistula River regime (R.Soja), a cartographer-analyst of river-channel changes over time (J. Plit), and two other geomorphologists, of which one is interested in studying the impact of regulation works on geomorphic processes (J.Warowna) and the other focuses on present-day sediment loads (A.Łajczak).

In contrast to other European rivers (Petts *et al.* 1989), the Vistula had a specific feature in the last few centuries. Its catchment area once constituting the central part of the Polish state was divided, in the late 18th century, between the three neighbouring countries of Austria, Russia and Prussia. Only in 1918 did it come back under Polish rule. Water management in the three countries in question differed greatly. Prussia was the first to start intensive regulation works in the lower course of the Vistula in the mid-19th century. At about the same time, after several major floods in the Upper Vistula catchment, the Austrian government started channelization works there. The longest (middle) reach of the Vistula River, left under Russian rule, remained practically unchanged (except in local fragments) until independence was regained. Even now, this segment of the river preserves many features inherited from previous centuries (e.g. braided channels and islands). This tripartition is still visible in present-day processes and forms, as being superimposed upon the natural sequence of processes along the longitudinal profile of the Vistula.

CHARACTERISTICS OF THE VALLEY, FLOODPLAIN AND CHANNEL

The Vistula River drainage basin, with an area of 199 813 km^2, is drained by a 1047 km long river. In what is an asymmetric drainage basin, right-bank tributaries predominate in both the upper reaches (Carpathian tributaries) and the middle reaches (Figure 1).

The Vistula flows across numerous morphotectonic units of diversified relief (Table 1). Particular sections of its valley differ in depth and width, the extent of the floodplain, channel width and gradient (Starkel 1990). A short Carpathian section of a narrow valley cut in flysch rocks has a gradient

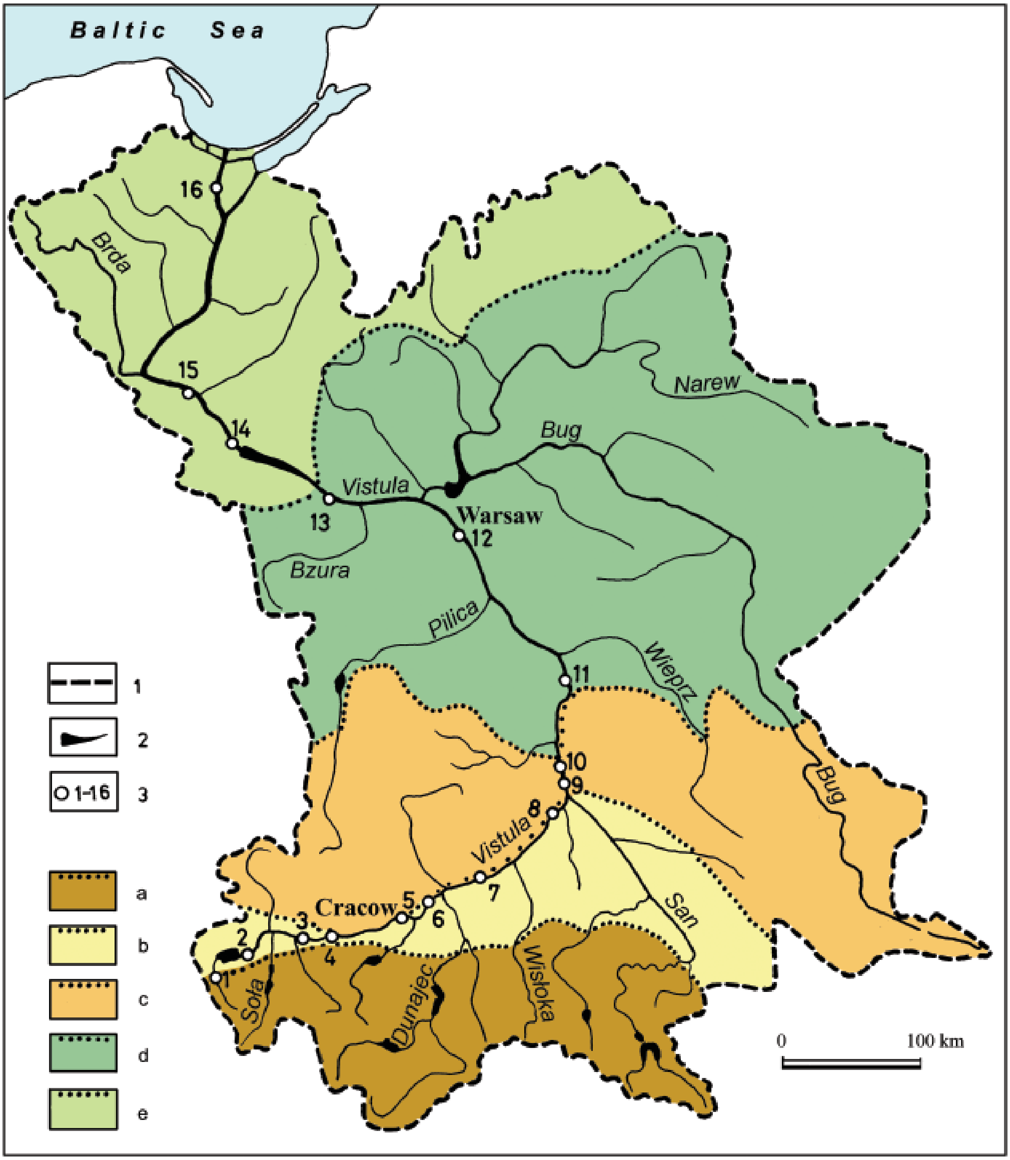
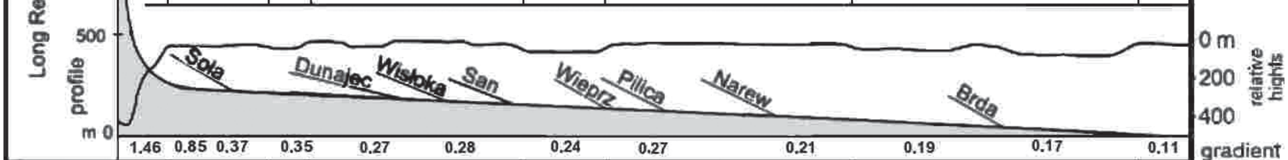


Figure 1. The Vistula River catchment against a background of geomorphic regions
1. main watershed; 2. water reservoirs; 3. hydrological stations mentioned in this paper
(1. Skoczów, 2. Goczałkowice, 3. Smolice, 4. Tyniec, 5. Sierosławice, 6. Jagodniki, 7. Szczucin,
8. Sandomierz, 9. Zawichost, 10. Annopol, 11. Puławy, 12. Warszawa, 13. Kępa Polska,
14. Włocławek, 15. Toruń, 16. Tczew).
a—Carpathians; b—Subcarpathian basins, c—Polish Uplands,
d—Polish Lowlands (Mazovian part),
e—Polish Lowlands (Kuyavian-Pomeranian part)

Table 1. Morphometric characteristics of Vistula Valley reaches



Long Region (reach)	Carpathians	Oświęcim Basin	Cracow Gate	Sandomierz Basin	Gap across Uplands	Polish Lowland: Masovian reach	Polish Lowland: Kuyavian-Pomeranian reach	Deltaic plain
Lenght of reach in km	36	70	35	170	75	215	260	44
Depth of valley in m	450 -100	20-40	40 -120	19-90	30-80	25-55	35-80	—
Valley width in km	0,1 -5	1-15	0,3 -41	8-25	1-15	12-20	4-20	>40
Width of floodplain in km	<1	1-5	0,3 -3	3-10	1-10	2-8	2-9	>40
Lenght of channel in km	40	109	46	208	86	246	275	45
Number of wide and narrow sections	1	2-1	4-5	5-4	1-2	1-1	4-1	

Source: Starkel (ed.)(1990)

of 14.6‰ on average. As the Vistula turns eastward, (in the Oświęcim Basin), the valley broadens, and the winding or meandering channel has a width varying from 20 to 50m. In the section considered, several tributaries merge with the Vistula. Over the next 35km section, the river flows across limestone horsts of the Cracow Gate, then along the northern margin of the Sandomierz Basin where it is shifted by the Carpathian tributaries. Here, in the river valley (8 to 25km wide), the Holocene alluvial plain is 3 to 10km wide. A regulated and embanked winding Vistula channel (once a meandering one), with a width of 100–200m tends to occupy the middle of the valley floor, albeit undermining the river left-bank plateaus in certain sections. At the confluence point with the river San, the Vistula turns northward and enters a gap across the Polish Uplands cut into limestones and gaizes. In the narrowed sections of the valley, the 1–2km wide floodplain occupies the whole floor, while in broader basin-shaped sections it is up to 10 km wide. The up to 1km wide channel has been braided before the last few decades. The Vistula then turns north-west and flows towards the Warsaw Basin (Mazovian Lowland), where it is joined by the river Narew and then turns westward. Here, the 0.5–1km wide braided Vistula channel uses one of the two marginal depressions. Downstream of the Bzura river, (a left-bank tributary), the Vistula starts its lower Kuyavian-Pomeranian reach incised in deposits from the last glaciation. The river channel gradient declines gradually to 0.1‰ and the valley confined by escarpments widens and narrows. The straight or winding river channel is only 300–500m wide, yet is regulated and embanked. The river flow is controlled by Włocławek Reservoir. The 45 km long outlet section of the regulated Vistula crosses the reclaimed area of the delta. The marked variability in relief of the Vistula valley—as controlled by lithology and tectonics, as well as the deglaciation pattern and spatial pattern of larger tributaries—has an unquestionable influence on the processes which have modelled and model its floor (Starkel 1990).

HYDROLOGICAL CHARACTERISTICS OF THE VISTULA

The complex hydrological regime of the Vistula is related to the location of its drainage basin in the transient temperate climatic zone. The dominance of a continental or maritime influences varies across an annual cycle, resulting in marked year-to-year variability in discharges. Depending on precipitation distribution in the drainage basins of the tributaries, hydrological parameters of the Vistula increase first rapidly but in an irregular manner to Zawichost (gauging station no. 9, see Figure 1), and then gradually in the downstream reach of the river.

Following the contribution by Fal *et al.* (1997), the hydrological characteristics are based on data from four gauging stations located along the Vistula River (Figure 2, Table 2). In winter, the river discharges increase steadily in the whole Vistula drainage

Table 2. Characteristic flows [m^3/s] at four hydrological stations along Vistula River, 1951–1990

Gauging station	Q_{av}	$Q_{av\ Nov.-Apr.}$	$Q_{av\ May-Oct}$	$Q_{max1\%}$	$Q_{min1\%}$
Nowy Bieruń	20.7	20.9	20.6	804	1.29
Sandomierz	292.0	294.0	289.0	7,500	54.70
Warszawa	573.0	614.0	533.0	7,400	102.00
Tczew	1,080.0	1,230.0	932.0	9,190	243.00

Source: Fal *et al*. 1997.

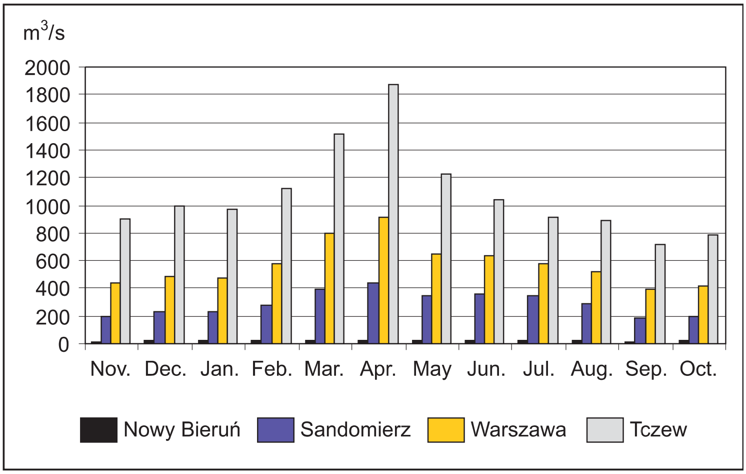


Figure 2. Mean monthly discharges of the Vistula River at four hydrological stations
Source: after Fal et al. 1997

basin from November through to the culmination of meltwater flow. From May, discharges decrease along the Vistula's whole length, yet the flow is always greater than the annual average. In the summer months (June–August), the second peak flow is related to extreme summer floods in the Carpathians. It progresses along the Vistula to Sandomierz (gauging station no.8, see Figure 1) and then ceases in the middle and lower reaches of the river. The lowest flows occur in September and are related to precipitation deficit and the small storage capacity of the drainage basin. Summer–autumn droughts take in the whole Vistula drainage basin. The mean annual flows increase from 6m^3/s in Skoczów to 21m^3/s in Nowy Bieruń, 292m^3/s in Sandomierz,573m^3/s in Warszawa and 1080m^3/s in Tczew (Figure 2). Winter flows predominate by 1% over summer-season flows to Nowy Bieruń, farther downstream by 7%, and finally by 14% in Tczew. This pattern reflects variable sources of water supply and a diminishing influence of the Carpathians downstream. In the Carpathian part of the drainage basin the river regime is controlled by heavy summer rain storms, with accompanying overland flow. Rainfall diminishes northward, permeable sandy covers store rainwater, and thus in the downstream section winter-season outflow predominates over summer.

The amplitude in Vistula water levels results from the presence of flood embankments, which cause the water level to rise in the intra-embankment area. In the Carpathian reach of the Vistula, without embankments and with a steep gradient, the water level amplitude is 2m, and cf. 3.5m in the foothill reach. On the other hand, in the area of Subcarpathian Basins this amplitude varies from 5 to 8.5m, depending on the gap between the embankments. Downstream of the San river mouth, in the broad channel, the amplitude of water level diminishes to 6–7m in Warsaw, while in Tczew it reaches its highest value of 10m. Over the whole length of the Vistula, the highest recorded water levels coincide with the heights of the embankment. Under natural conditions, (i.e. prior to straightening and deepening of the Vistula channel), water-level amplitude was possibly only half as great (Makowski and Tomczak 2002).

The Vistula is a river with high and frequent summer floods triggered by continuous rainfall in the Carpathians and their foreland (Figure 3). The flood of 1813, which occurred across the whole Vistula drainage basin, is believed to have been the most spectacular in the whole period for which observations were carried out. The floods of 1844, 1903, 1839, and 1934 were of a slightly smaller magnitude. The flood of 1997 was characterized by the highest recorded discharges at the majority of the Vistula's water-level gauging stations to Zawichost. The analysis of water levels in the lower reach at Toruń (gauging station no.15, see Figure 1) since 1770 points to the occurrence of some years without significant floods (5–8 cases in a century), as well as a few years recording 2 or 3 high floods (Makowski and Tomczak 2002). Spring floods, which occur regularly, predominate, while summer and winter floods are less frequent.

Flood waves formed in the Carpathian part of the Vistula drainage basin reach their maxima at Sandomierz or Zawichost, before being quickly flattened downstream such that only occasionally does the peak flow increase to the river mouth (as in 1962, Figure 3). The summer flood of 1997 had a discharge of 2000m^3/s in Cracow, 5830m^3/s downstream of the Dunajec river mouth, 5800m^3/s in Sandomierz, 4730m^3/s in Warsaw, and 4220m^3/s at Tczew (Barczyk *et al.* 1999). The increase in maximum discharge values, resulting from superimposed flood waves of the Vistula and its tributaries, usually occurs in the Sandomierz Basin. The peak discharges might be altered through embankment breaking and the formation of an episodic flood lake. An inundated area in excess of 300 km^2 was formed during the summer flood of 1934.

Extreme snowmelt floods (Figure 4) occur less frequently than the rainfall-induced ones, though in this case the maximum discharges increase steadily down the river. In 1979, the peak discharges of the Vistula were 1290m^3/s at Sandomierz, 2550m^3/s at Warsaw and as much as 7020m^3/s at Tczew, the result of a superimposed flood wave of the Vistula and the thawing flood waves in the Bug and Narew drainage basins. Ice-jam floods occurred very often in the past. However, the channelization of the Vistula River in the last 150 years, as well as thermal and chemical pollution of the water, reduced ice-jamming. On the other hand, frazil-ice-jams began to form in backwater areas of the reservoirs.

The highest observed Vistula discharges reached 7450m^3/s at Zawichost ($Q_{1\%}$ is 8160m^3/s at Zawichost, according to Punzet 1991) and 8000m^3/s at Tczew. However, if the first peak flow resulted from a rainfall flood, the second was due to a snowmelt flood. The 1% water flow corresponds to a specific runoff of 460 l/s/km^2 at Nowy Bieruń, 236 l/s/km^2 at Sandomierz, only 88 l/s/km^2 at Warsaw and 47 l/s/km^2 at Tczew. The frequency of floods (p%) was calculated using the log Pearson type III distribution applied by Polish hydrologists (Punzet 1991). In case of the Vistula basin the extreme floods in the upper and middle course of the river are generated by summer rainy floods in the Carpathians and downstream the Narew junction mainly by snowmelt floods.

In the 20th century, the mean annual outflow from the Vistula drainage basin did not show statistically significant trends (Fal 1993). Studies on changes in the flood regime of the Vistula River and its major tributaries have been performed many times. The obtained negative regression coefficients referred to peak flow and the frequency and duration of floods in the years 1901–1970 (Stachy and Nowak 1977). Similar results were found when examining the variability to extreme annual discharges in the years 1921–1992 (Stachy *et al.* 1996). In the medium-size catchments of the Carpathian part of the Vistula basin, there is a trend towards a decrease in flood magnitude (Soja 2002), but there is a steady increase in minimum discharges related to reservoir management. In general, the hydrological regime of the Vistula River in the 20th century has been characterized by a decrease in the number of floods. Nevertheless, catastrophic floods have occurred, some of these being clustered in subsequent years, but then followed by 15–20-year periods without major floods (Starkel 2001).

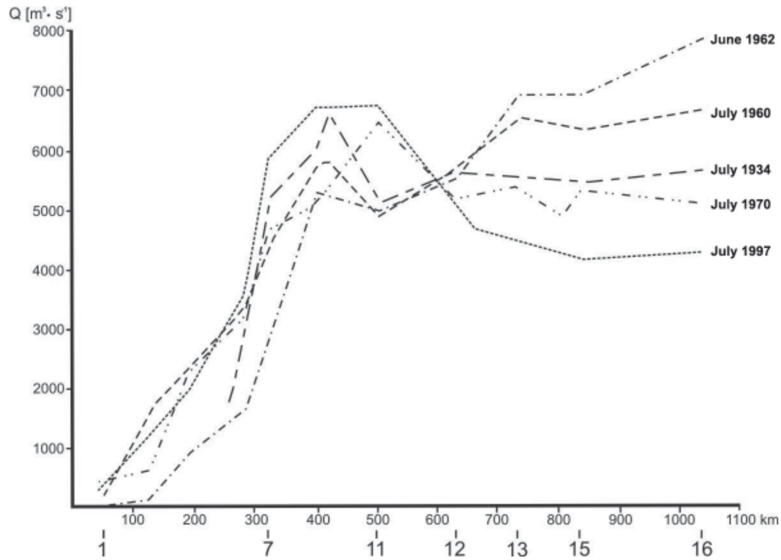


Figure 3. Maximum discharges in the longitudinal profile of Vistula River during summer rainy floods
Source: based on Soja and Mrozek in Starkel (ed.) 1990

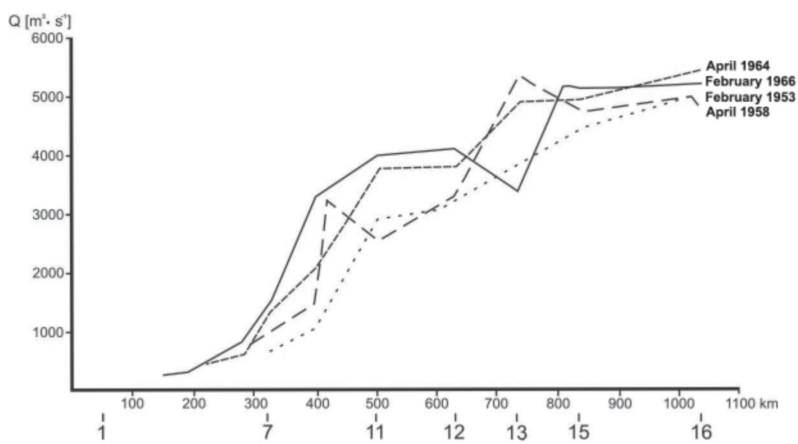


Figure 4. Maximum discharges in the longitudinal profile of Vistula River during snowmelt floods.
Source: based on Soja and Mrozek in Starkel (ed.) 1990

PROCESSES IN THE REGULATED VISTULA VALLEY—CHANGES IN THE PATTERN AND SHAPE OF THE RIVER CHANNEL

THE UPPER REACH: FROM SPRINGS TO THE SANDOMIERZ BASIN

Apart from in the short mountainous section, the Vistula valley become deforested, farmed and densely populated. Analysis of the three maps dating from the turn of the 18th century to the mid-19th century[1], shows that the Vistula formed its channel freely on a valley floor of diverse width. At that time, it was a meandering, unregulated river (excluding the section within the city of Cracow). The river upstream of the Cracow Gate had meanders of small (50–200m) radii, the channel being 140–170m wide.[2] Downstream of Cracow to the Dunajec outlet, the Vistula channel was very winding, with small-radii meanders (300–400m). The old maps do not depict larger bars and natural levees. Downstream of the Dunajec river mouth, the Vistula was 400m wide, bars occurred in the channel and the meander radii were larger (500–600 m).

From the beginning of 19th century, the section upstream of Sandomierz was characterized by accumulation, the channel became shallower and wider, and numerous bars and islets were formed. In the mid-19th century, the channel changed gradually in the reach between the mouths of the Dunajec and San rivers. Although the Vistula still flowed in a sinuous channel, the river was shallower; it occupied a wider channel and had left numerous bars. Numerous distributaries and abandoned channels occurred. The crucial transformation was related to embanking and straightening of the river channel (Figures 5, 6). In the years 1800–1980, the upper Vistula was shortened by 34,3km in the Oświęcim Basin (Czaja et al.1993) and by 35,5km in the Sandomierz Basin (Trafas 1992).

The channelization works started in various reaches of the Vistula at different times. In the Carpathian part only one reservoir (Czarne), with a capacity of 4.5 million m³, was built in 1974. A series of concrete sills have been constructed to prevent downcutting. The next reservoir (Goczałkowice), on the flat floor of the Oświęcim Basin, is up to 14m deep and 11km long, and accumulates all bedload and a majority of suspended load. In the area of the Oświęcim Basin the Vistula preserved its winding character, despite the channelization in the 1920s, when the river channel was shortened by 40%. As a result the channel gradient increased from 0.34‰ to 0.56‰ (Czaja *et al.* 1993) and downcutting has been activated. In the 1950s, the construction of a cascade of dams with canal locks in the region of Cracow inhibited the process of intensive downcutting which has been observed since the mid-19th century. Ingarden (1922) estimated the channel deepening at 2.5m, while Punzet (1981) reports the value of 3m for the period of 1871–1954. Such extensive erosion was supported by the cutting and filling of the abandoned channels (these playing the role of bypass channels), and by exploitation of sand from the river bed up to 1950.

In the Sandomierz Basin, channelization works entailing cutting of river bends started in 1848. At the same time, the channel was narrowed by a system of dykes and groynes. The gradient thereby increased from 0.28 to 0.32‰ (Trafas 1992). In the second half of the 20th century, the erosion rate of the Vistula channel bottom was ca. 1 cm/year. The channel sinuosity in the Upper Vistula dropped from 1.7 to 1.4 (Babiński and Klimek 1990). The downcutting is reported to reach from 0.5 to more than 1m (Ingarden 1922, Punzet 1981). The cutting works resulted in river bends of large curvature—extending the radius to 1km (Trafas 1992).

[1] Detailed Map of the Polish Kingdom provinces of 1783 (*Mapa szczegulna wojewodztw koronnych*) of Karol de Perthès, scale 1: 225 000, *Regna Galiciae et Lodomeriae Josephi II et M. Theresiae...* of 1790 of Joseph Liesganig, scale 1: 28 800 and *Carte von West-Gallizien..* of 1808 of Mayer von Heldensfeld, scale 1:172 000.

[2] Measurements based on Übersichts Plane Weischel Stromes… 1:14 400, manuscript map of 1851–1852.

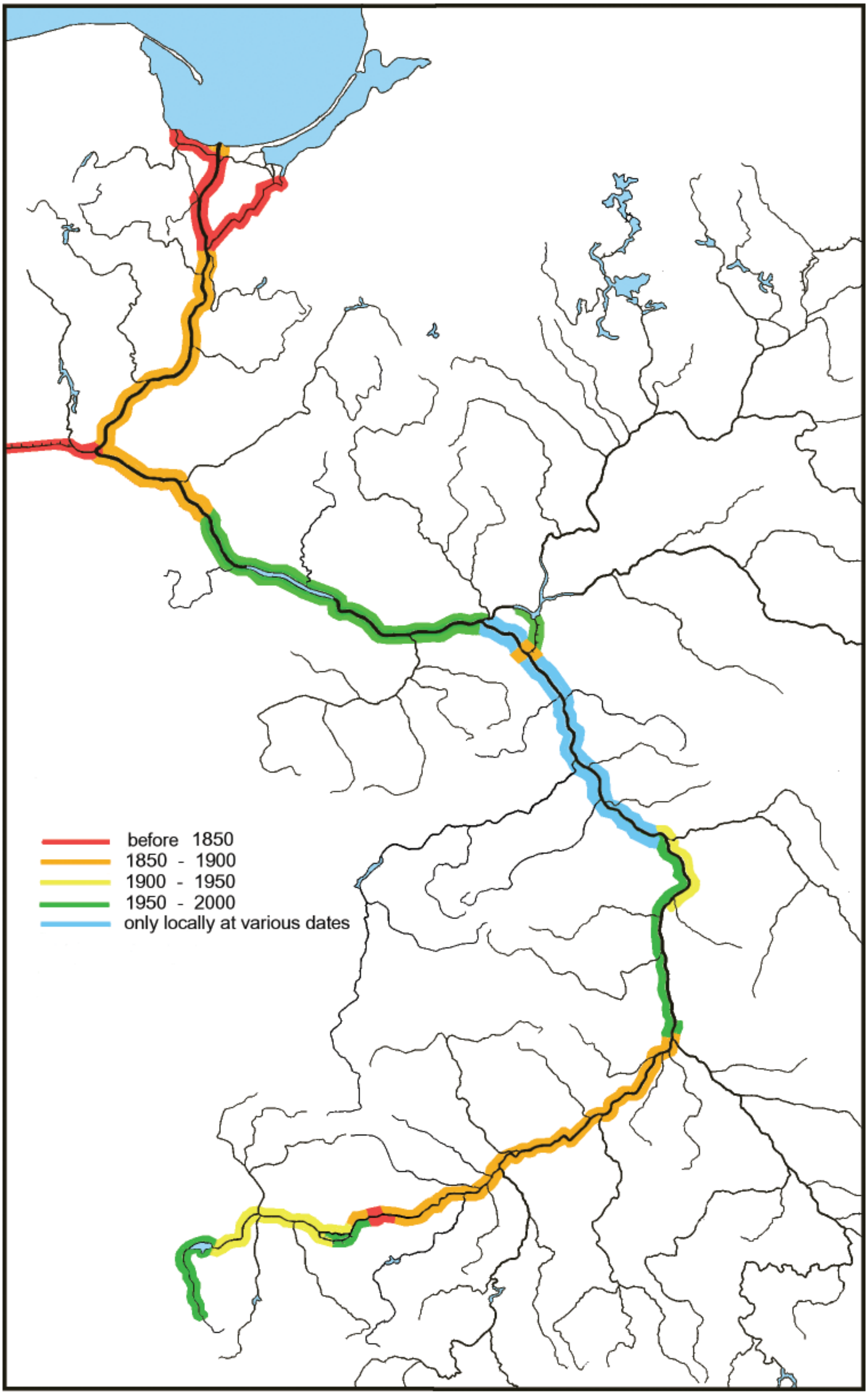


Figure 5. Times of regulation of the Vistula River channel
Source: elaborated by J.Plit and J.Warowna

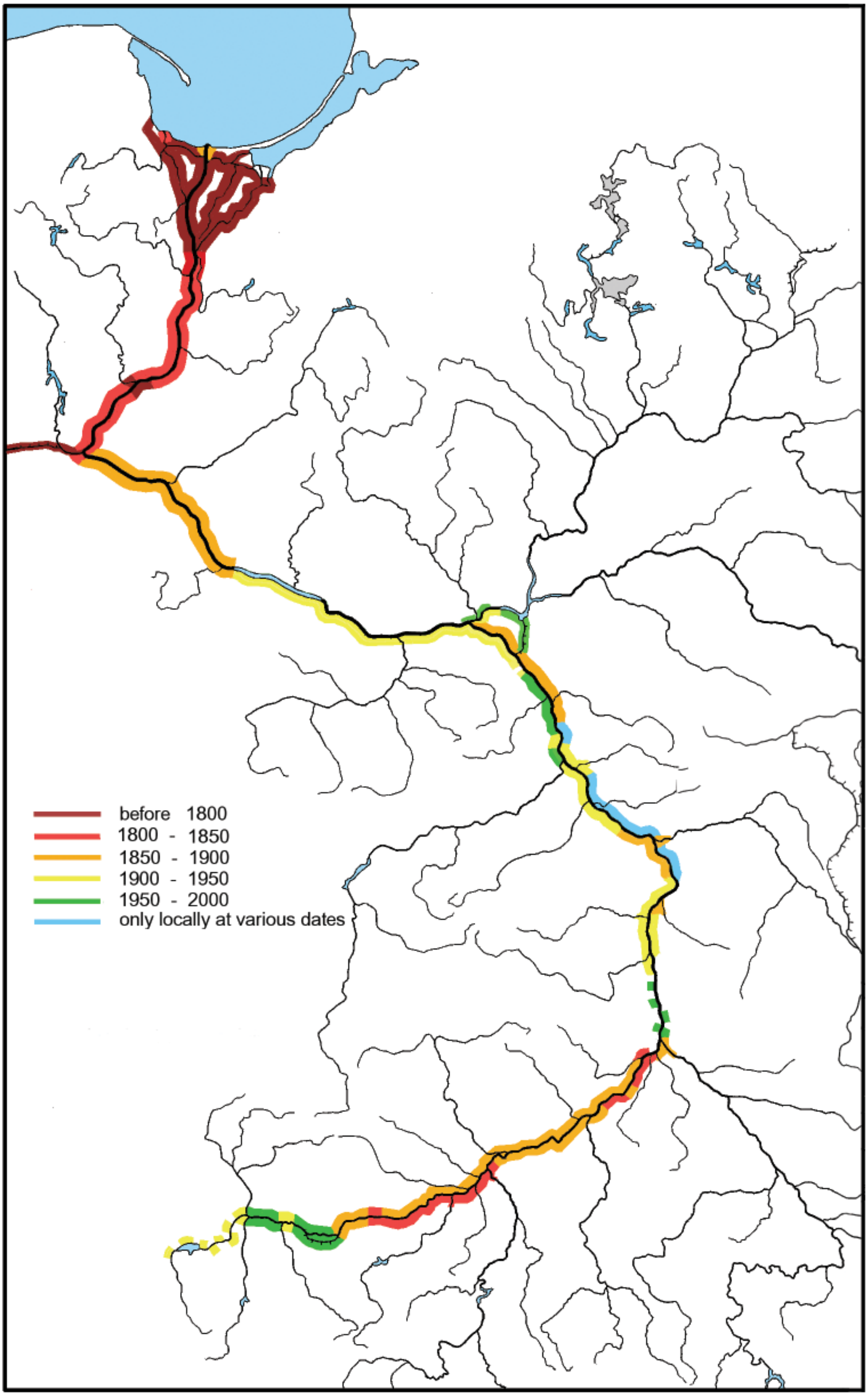


Figure 6. Times of embankment of the Vistula River
Source: elaborated by J.Plit

The substantial narrowing of the flood channel resulted in repetitive breaking of flood embankments and the formation of crevasse splays (Gębica *et al.* 1998).

THE VISTULA IN THE GAP THROUGH THE UPLANDS

The Vistula valley in the gap section (see Figure 1 and Table 1) was continually deforested from the Middle Ages on. Channel mobility depended on valley width. At sites where the valley was narrower, the river was confined in the same location. Still at the beginning of the 19th century, the Vistula meandered in certain sections, and flowed in two or three parallel winding branches. The main channel shifted from one bank to the other. Numerous islets stabilized by vegetation were formed at that time. The abandoned meanders or flood channels of the Vistula were often used by the tributaries (Kalicki and Plit 2003).

Changes in river character occurred in stages, especially after the series of large floods in the 19th century. The river deposited numerous bars, formed islands, and occupied an extensive area. The width of the meandering channel was 100–200m, while that of the braided channel was 300 –1500m (Warowna 2003). The average annual rate of bank erosion was 3–9m.

In the 19th century, an increase in the size of particles deposited on the floodplain ((from mud to sand) was recorded (Falkowski 1967), and a change from a sinuous channel to a wide, shallow and straightened one with shifting bars. This transformation resulted from accelerated outflow of water and sediment load through the channelized reaches of the Upper Vistula and tributaries (Warowna 2003). The sedimentation of sand in the upper part of the gap reached 1m (Falkowski 1967). The channelization works performed partly in the 1920s and later between 1960 and 1990 resulted in a narrowing of the mean water level channel (by a system of dams and groynes) to 120–300m and to the cutting off of side branches by dykes (Figure 7). The width of the bankfull channel is 500–600m. The lateral erosion was limited to short, non-channelized reaches (locally reaching 20–100m in 1980–2003) and to the formation of bank failures, which are several meters deep and tens of meters long, to the leeward of dykes. Sandy material transported as bedload was accumulated between the artificial structures in the intra-groynes areas. Based on the volume calculation, the average sedimentation rate was 1.3 million m^3 per year. The polders have filled up to 2m above mean water level and a new man-made terrace is being formed. This floodplain terrace may be up to 350m wide. Its flat surface is slightly inclined towards the river or raised as a levee-like form near the channel, and, then, descends towards the natural flood plain where backswamps occur. The intra-groyne sedimentation is accompanied by downcutting in the active channel axis. Evaluation of the incision rate is hindered by migration of the bed bars, which causes fluctuations in the floor heights of up to 2m per year (Warowna 2003). The presence of groynes results in the formation of potholes up to 12m deep.

THE VISTULA VALLEY IN THE MAZOVIAN REACH

After leaving the gap, the Vistula used to transform its main channel, chiefly in the locations where the valley widened. As recently as in the 18th century, the Vistula was still meandering in the central section up to the confluence with the Narew. After the flood of 1813, the Vistula used 2, or more rarely 3, branches. In certain sections it became a braided river with channel width reaching 1000m (Plit 2004). Over the last 250 years, the width of the belt where the channel shifted was 1–4 km (Falkowski 1967). This process was limited artificially to the intra-embankment width in the 19th century (Figure 6). The narrowed sections of the valley are related to the presence of rocks resistant to erosion (clays mainly) and are characterized by a deeper channel and strong lateral erosion. The embanking of the river was performed successively, section by section. It started after the catastrophic floods in 1844 and 1888/1889, but the undertaking was ended after the Second World War.

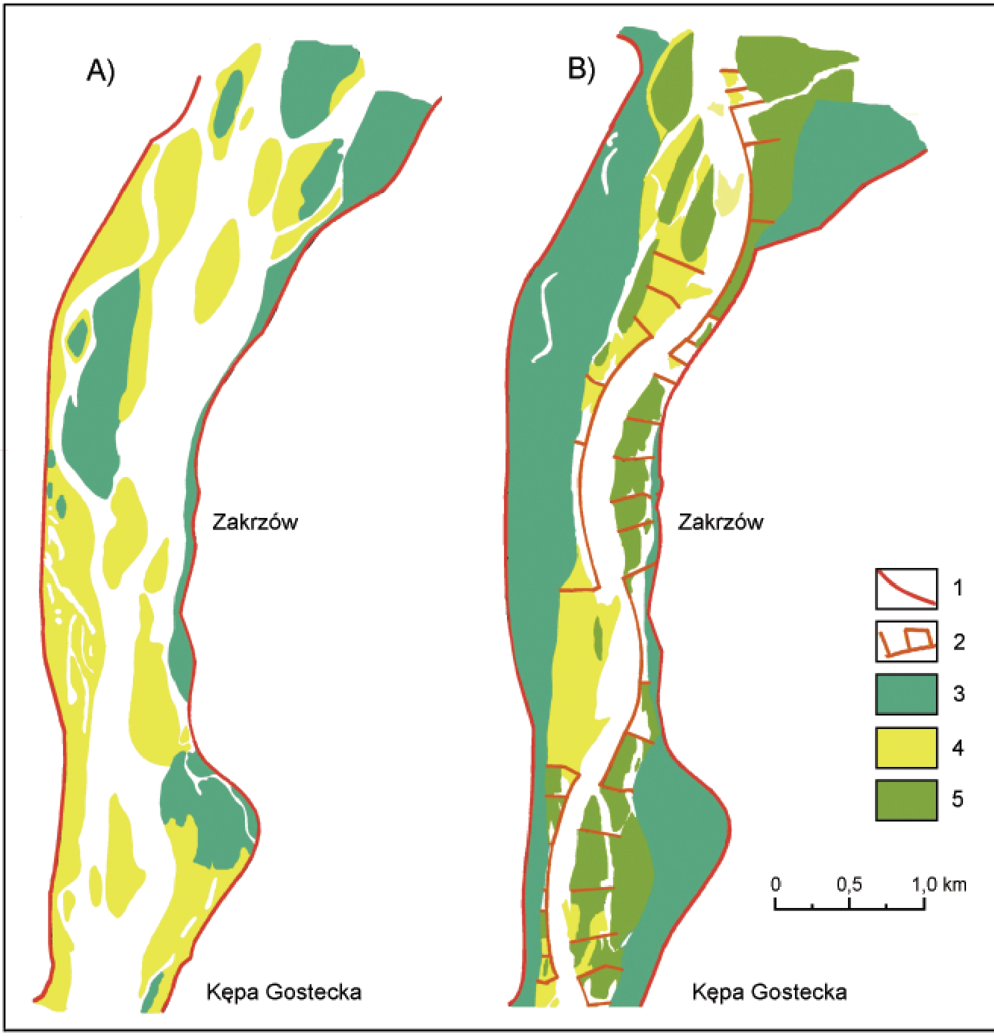


Figure 7. Changes in channel and floodplain form caused by the regulation in the middle course of the Vistula River between 1960 (A) and 1995 (B).
1—embankments, 2—various regulation constructions, 3—bars revegetated before 1960, 4—active channel bars, 5—bars revegetated after new regulation works.
Source: elaboreted by J. Warowna

Antierosional protection was provided for bridge pillars, industrial plants and the urbanized area of Warsaw. In this reach, the lateral erosion may rise to 4–5m per year. In Warsaw channelization started after the flood of 1884, when the river channel shifted 500m eastward. The reach was regulated by longitudinal works and rip-raps, so the channel narrowed from 500–700m to 340m. Successively, particular side branches were cut off, so the whole flow concentrated in one main channel. Due to highly resistant clay deposits exposed in the bottom, downcutting does not occur despite the fact that the channel is narrowed (Jacewicz and Kuźniar 2000).

In the 18th and 19th centuries, the lower Vistula downstream of the Narew mouth was a braided river with bars and islands. Two or rarely three parallel troughs functioned in short sections in the 19th century. On the valley floor the series of troughs, which evidence a parallel shifting of the river, are preserved. Abandoned meanders occur only locally, in places where the valley widens. In this area, which was under Russian rule up to 1918, the first flood control structures and regulation works had been initiated by the end of the 19th century (Babiński 1992).

The reach downstream of Warsaw, where singular groynes do not modify the braided pattern of the river, was not channelized until the 1960s. At present, the mean flow channel has been narrowed to 300m. The primary width of the braided river bed was 1.1–1.6km, with a mean water table width of 0.6–0.9km. The patterns of the side bars and river current vary and 60% of the bank lengths are eroded. Migration of the channel bars follows at a rate of 0.6–1.4m/day (Babiński 1992). However, the construction of the reservoir in Włocławek in 1969 modified the ongoing processes. The backwater affects a 58km section upstream of Włocławek. The amplitudes in the water table reach 2.2m. The lateral erosion has give way to abrasion and mass movements (affecting 45% of bank lengths), which were most intensive in the first years just after reservoir construction. The edge of the morainic plateau retreated by 150–200m in places. After the ice-jam flood of 1982, the low inundated islands have been removed and up to 1.5m high sandy-gravel protective benches have been set up along 15% of the banks (Banach 1994). The reach below Włocławek was channelized in the 1950s, but ca. 25% of the banks are eroded at present (Banach 1998). Downstream of the reservoir, downcutting reached 2–3m in the first 20 years, over a distance of 3km from the dam. Downstream erosion is ceasing gradually (Babiński 1992). Armouring of the bottom with cobbles is a protection against the ongoing erosion. Accumulation forms appear just 25km down from the dam. The material building those forms is much coarser when compared with that known from the pre-reservoir years.

The formation of an ice cover, flow of ice floes and ice jams are independent factors modelling the bottom and banks of the channel (Grześ and Banach 1983) The shores of Włocławek Reservoir are deformed by thermal expansion of ice causing ice-plough ridges to form. Those ridges can be several tens of centimetres high and up to 1.5m wide (Banach 1994). The ice floes drifting downstream damage the unregulated banks, while ice-jams divert the current towards the distributary troughs, reactivating them or triggering downcutting downstream of a jam. It is believed that still-existing unregulated river reaches are ice-jam generating.

THE VISTULA VALLEY IN THE KUYAVIAN-POMERANIAN REACH

The first regulation of the partly braided and partly anastomozing lower Vistula in the areas formerly under Prussian rule was performed in the 18th century. The hydrotechnical works comprised the construction of groynes and dykes or rip-raps, the clearing of the willow thickets from the channel, the levelling of the bottom and narrowing of the channel, the shifting of the river bed and the construction of a canal connecting the Vistula and Oder rivers. Modernization and banking up ended in 1880–1892.

Up to the end of the 19th century, it was accumulation processes that occurred, then regulation followed. Channel deepening was intensified after the shortening of the outlet to the Baltic Sea in 1840, and in the years 1895–1915. The deforested floor of the Vistula valley was then used as farmland and meadows. Frequent catastrophic floods in the 19th century caused people to abandon settlement and cultivation in the floodplain.

The Lower Vistula was channelized systematically in the last 25 years of the 19th century (Figure 4). The regulatory measures were miscellaneous. The channel was narrowed to 350 –375m, but in the delta both branches were narrowed to 250m and 125m, respectively. Accumulation of the sandy-silty deposits in polders between the groynes and on the regulation structures reach 3.4– 4.2m above the river level (Szmańda 2000). The channel capacity decreases, because the deposition at the channel banks is larger than the volume of the eroded material. The man-made terrace is 375–450m wide (Babiński 1992), and is higher in the narrowed parts of the channel. The formation of levees 2–20m wide and up to 1m high, which separate decantation pools up to 1.8m deep and 36m wide, is observed. The mean depths of the channel upstream of Fordon were 1.6–2.0m (at widths of 730–780m) prior to channelization, but the minimum depths decreased to 0.7m. Since the mid-1970s, depths have been reaching 3.0m. As a result of the channelization, this section of the river is straight, with alternating bars and pools.

THE VISTULA DELTA

The Vistula delta has been deforested for centuries, subjected to intensive farming, and dissected by a dense network of artificial drainage canals. Both the rivers and the canals were embanked. At the beginning of the 19th century, the Vistula entered the Baltic sea using three branches. The majority of flow was concentrated in the right branch. According to Majewski (1969), in the 19th century, this branch of the river used to shift the landline 25–30m offshore per year. The embankments confined accumulation to the intra-embankment area and to the fans, explaining why the Vistula channel is located higher than the surrounding plains. The delta was inundated very often. Snowmelt floods were particularly hazardous, as the flood wave entered the still-frozen lower Vistula and the Gulf of Gdańsk. In February 1840, the left branch of the river was ice-jammed. The flood wave formed a new outlet route ca.14km shorter, which started to form a fan-delta quickly, while the accretion of the old delta was hindered. Some hazardous floods (especially ice-jammed ones) in the 1880s, forced a 9km long shortcut and the formation of an artificial outlet allowing 90% outflow of Vistula water. Higher embankments were built and the intra-embankment area broadened. The original natural outflow routes were abandoned (Makowski 1997). Once development work ended, river alluvia ceased to fertilize the delta. Accumulation in the form of an underwater delta occurs at the bottom of the Gulf of Gdańsk.

THE ROLE OF FLOOD EMBANKMENTS

Construction of the flood embankments and confining of the peak flood flow zone has been carried out progressively since the mid-19th century (Figure 6), although long embankments have been present in Żuławy since the beginning of the 14th century (Makowski 1997). In the Upper Vistula, the gap between the embankments is of 600–800m (Czajka 2000), increasing to 900–1500m downstream of the junction with the San. However, this zone shrinks to 600m occasionally, due to bridging, or to 450m, if the old embankments are located closer to the river channel. In the Mazovian Lowland, the width of the intra-embankment area is 1000–1700m, excluding within Warsaw where it is narrowed to 400–600m (Jacewicz and Kuźniar 2000). Downstream of Włocławek, the gap between the embankments is 1000–1500m. Reduction of the flood sedimentation area to 25–40% of the primary one causes fast aggradation in the intra-embankment area, and the formation of a new terrace level in the channelization zone (Warowna 2003). In the Oświęcim Basin, accretion of a 1.5m thick layer has been noted since the 1950s (Czajka 2000). If the embankments are broken, as during July 1997, flood crevasse troughs up to 300m long and 10m deep form, as well as crevasse splays to one kilometre long and 0.7m thick (Gębica *et al.* 1998).

SEDIMENT TRANSPORT, DEPOSITION AND LOADS

The north-facing slope of the Carpathians is the major source area of material supplied to the river as dissolved and suspended loads

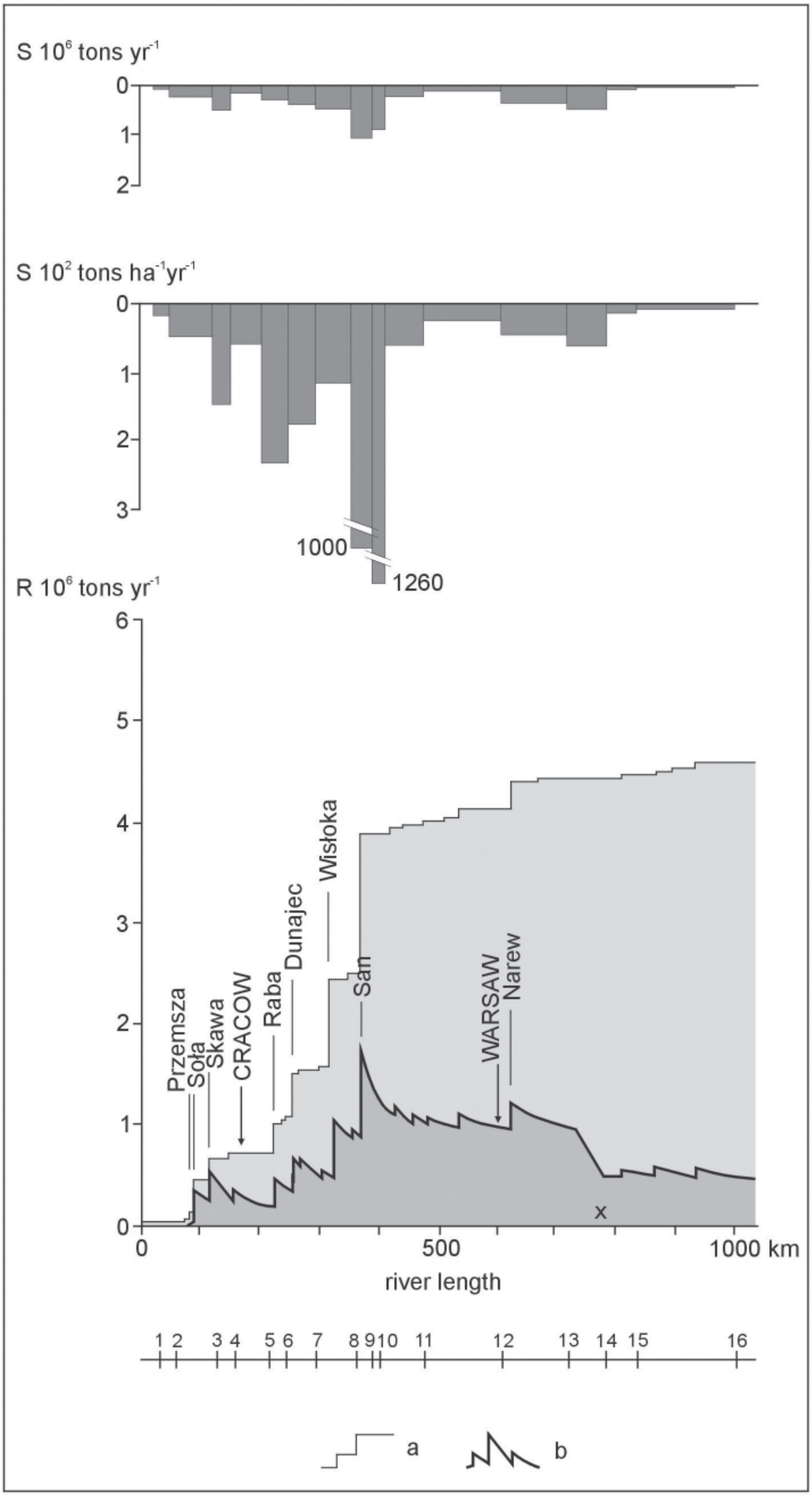


Figure 8. Differentiation of mean annual suspended load R (in tons) along the Vistula River between 1946 and 1995.

and as bedload (Brański 1974; Maruszczak 1984; Łajczak 1999). The role of the Polish Uplands in this supply is less significant, the lowland area making a minor contribution. The average suspended load transport in the Carpathian, upland and lowland parts of the Vistula drainage basin is of 200, 10 and 3t/km^2 per year respectively, while the average dissolved loads are 100, 60 and 45t/km^2 per year (Maruszczak 1984; Łajczak 1999). Only in the mountain area of the Vistula drainage basin does suspended load and bedload transport predominate. In upland and lowland terrain, the level of ionic transport is several times greater than suspended-load transport. In the mountain and upland tributaries of the Vistula and the stretch of the main river in the Carpathian foreland does suspended material dominate the bedload load (Brański and Skibiński 1968; Froehlich 1982).

The rate of suspended-load transport offers only indirect evidence of erosion intensity in a catchment. Downstream in a river, any estimation of erosion magnitude in the drainage basin becomes more and more difficult. The losses in transported suspended load are expressed by reference to the sediment delivery ratio (DR), which indicates the percentage of entrained material which flows out at a gauging site. This ratio decreases downstream, and in sub-catchments of the order of 10^2–10^4 km^2 in area it reaches from a few to a dozen percent (Maruszczak 1984). In the mountain catchments this ratio is higher. In the small catchment of a stream, cart tracks and forest ways can supply about 80% of the suspended load to that stream (Froehlich 1982; Froehlich and Walling 1992). On the scale of the whole drainage basin of the Vistula, DR does not exceed 1% as a result of the presence of many reservoirs. The contribution of suspended load to the overall transport of clastic material shows a downward trend downstream in the Upper Vistula, and varies from 90% to 70%. In the lowland tributaries, suspended-load transport amounts to 50%, if 23–28% in the lower Vistula, according to Babiński (1992). The examination of the grain-size composition of deposits in the Carpathian reservoirs confirms the dominance of clay-silty particles (Łajczak 1999). In Włoclawek Reservoir, the silty-clay deposits only dominate in the deepest parts.

The mean annual suspended-load transportation in the Vistula increases suddenly at the mouth of tributaries, and then decreases between river junctions (Figure 8). Among the Carpathian tributaries, the San supplies the largest load to the Vistula, i.e. 0.8 million tons per year. The greatest transport of suspended load occurs in the stretch of the Vistula downstream of the San river mouth, where the average load was ca 1.6 million tons in the second half of the 20th century. The magnitude of the transported load prior to dam construction was estimated at 2.3 million tons (Łajczak 1999). In the lower reach of the Vistula, prior to construction of the Włocławek Dam (in 1968), the magnitudes of transported loads were steadily graded over the whole length of the river. After the reservoir came into use, the magnitude of the load decreased to 0.5 million tons.

The magnitude, seasonal and multi-annual pattern of transport and sedimentation in the Vistula have changed drastically due to human impact. Significant changes occurred in the 20th century due to chanelization works and the setting up of hydrotechnical structures (Łajczak 1995, 1999). The total supply from the tributaries was

a—hypothetical sediment load (without depositional effects), b—real sediment load
S—mean annual deposition (in tons/yr and tons/ha/yr. in the balanced reaches (calculation based on difference between successive measuring points). On the longitudinal axis indicated 16 hydrological stations (see Figure 1) and position of the dam in Włocławek.
Source: elaborated by A.Łajczak

of ca 3.6 million tons per year in the second half of the 20th century, the upland tributaries supplying 0.4 million tons per year and the lowland ones 0.5 million tons.

In the annual cycle, suspended-load transport in the Upper Vistula predominates in the summer months (June–August) over the spring months (March–April). The influence of the mountain tributaries decreases downstream. Therefore, in the middle reach of the Vistula, the early spring and summer transported load are similar, while in the lower reach it is spring loads that predominate. Downstream of the dams, transported loads have started to even out during a whole year.

The effects of human impact are most noticeable when multi-annual changes in suspended load transport are analyzed. Upstream of the Cracow surroundings large changes in transport in the second half of the 20th century were related to the supply of physical pollutants to the river (mainly from coal mines via the Przemsza river). The size of the suspended load increased up to 1970, reaching double the value of the period 1946–1950 (from ca 0.2 to 0.4 million tons respectively). Up to the mid-1980s, suspended-load transport decreased rapidly, the following years bringing a stabilization at a lower level than before 1950 (Łajczak 1999). Downstream of Cracow, up to the mouth of the river, the suspended load transport showed a downward trend. This is related to a larger number of reservoirs set up and to changes in land-use (a reduction in the area of arable fields). The most significant decrease, by a factor of six, occurred in the lower reaches of the San river in 1946–1995, as an effect of significant changes in land use within the river catchment post 1947. Despite human induced changes, the influence of hydroclimatic factors on the multi-annual pattern to suspended load outflow is still evident. In the Carpathian tributaries and along the whole course of the Vistula to its mouth, almost decade-long fluctuations in suspended load transport result from the major floods which occur every few years.

The suspended load settles partially on the floodplain during floods (in the intra-embankment area at present) and in reservoirs. The average annual losses in transported load attest to intensified overbank sedimentation and have been calculated for successive river reaches between the gauging stations, according to the input-output method, for the period 1946–1995. They show an upward trend along the whole Upper Vistula (Figure 8). These losses diminish considerably downstream, and only beyond the Narew mouth and in the backwater stretches of the Włocławek Dam are they larger. Accepting that, since the beginning of the 20th century it is channel deepening, initiated by channelization, that predominates, the accumulation of suspended load can only be related to the intra-embankment area. The overbank accumulation increases along the Upper Vistula and reaches almost 1000 tons/ha beyond the San confluence. This fact is confirmed by the complete filling of abandoned channels, which were cut off there at the beginning of the 19th century, and by accretion of the Vistula floodplain in the gap stretch (Maruszczak 1982; Łajczak 1999). In contrast, the morphology of older abandoned channels of the Vistula located upstream is still visible. In effect, shoaling of this reach of the Vistula takes place and results in prolonged overbank flooding leading to greater floodplain sedimentation (Łajczak 1999; Warowna 2003). In further stretches of the Vistula, to its mouth, overbank sedimentation decreases to ca 10 tonnes per ha per year, and just between the Narew river outlet and the dam in Włocławek it exceeds 50 tons per ha per year. Repeated surveying indicates that the accumulation of suspended load in the intra-embankment area occurs at the highest rate in the zones occupied by natural levees, and at the lowest rate in the vicinity of the flood embankments.

Two reservoirs on the Vistula River play an important role in sediment storage. The Goczałkowice Reservoir, stopped storing suspended load durably after 20 years in operation, though it captures the entire bedload. The Włocławek Reservoir stores half of the incoming suspended load and the entire bedload. The influence of this reservoir on the transport of suspended load in the lower reach of the Vistula has varied over time, depending on reservoir shoaling and dragging. Small dams on the Vistula River near Cracow hardly stop suspended load at all. The most significant reduction in sedimentation, even by a factor of five, has been noted downstream of the mouths of tributaries on which deep reservoirs are located.

CONCLUSIONS

From its mountain reach, via the fore-mountain basins and the upland belt, as well as through the lowland zone down to the delta at the outlet to the Baltic Sea, the Vistula valley is currently modelled by a river whose hydrological regime is complex. Besides the summer floods related to extreme rainfall occurring in the mountains, thawing floods also occur and are often combined with ice-jams (such floods becoming more significant downstream in the river). The floods triggered in the mountains lose their impetus in the foreland, where the inundating rivers leave behind a considerable load of transported material.

The significant deforestation of the drainage basin prior to the 19th century led to a change from a meandering to a braided channel pattern in the Upper and Middle Vistula and to a change from an almost anastomosing or winding pattern to a braided one in the lower reaches. Ice-jam floods, especially in the middle reach, have resulted in channel shifting and avulsion in widened sections.

Channelization started in the mid-19th century in the areas which were formerly under Austrian rule (the upper reach) and Prussian rule (the lower reach). This resulted in channel braiding in the middle reach, as well as progressing delta aggradation and simultaneous channel deepening in regulated reaches (Figure 9). Since the beginning of more extensive channelization in the first three decades of the 20th century, a general increase in transport and in overbank sedimentation due to channel deepening has been observed. In the following decades, the rates of transportation and sedimentation declined as more deep reservoirs were constructed. The channelization and simultaneous intensified chemical pollution caused the natural Vistula River to take the role of a canal directing the water surplus out of the drainage basin. The diversity of channelization works undertaken in the second half of the 20th century, combined with the setting up of reservoirs and dams on the Vistula and its tributaries, brought about changes in the size of transported and deposited material, and in effect, aggradation in the intra-embankment zone at many locations, the formation of a man-made terrace and an exceedance of maximum water stages hazardous to the whole floodplain (Figure 7). The role of major floods has become more important, so the unconstrained flow and river load transport over the whole river length are possible only during extreme floods, while aggradation can occur on the whole floodplain. The milder winter seasons (with a lesser hazard due to thawing floods) seem to influence the transportation of the river load positively. Ice-jam floods occur rather rarely, due to severe water pollution and a rise in water temperature. On the other hand, the power-generation function of the reservoirs has a negative influence on flood control safety. The Vistula floods downstream of the Włocławek Reservoir which occurred in 1982 and at the beginning of April 2006 are good examples here.

The changes in land-use (especially reduction in arable area) observed in the last 20 years favour decreases in suspended-load transport and in aggradation. The summer floods favour channel-deepening in the upper reaches of the rivers, but simultaneously increase the hazard of sudden floods downstream. This may lead to changes in valley-floor management, and to more rigorous compliance with water management rules. The widening of the intra-embankment zone and withdrawal of settlements and infrastructure from flood areas will become

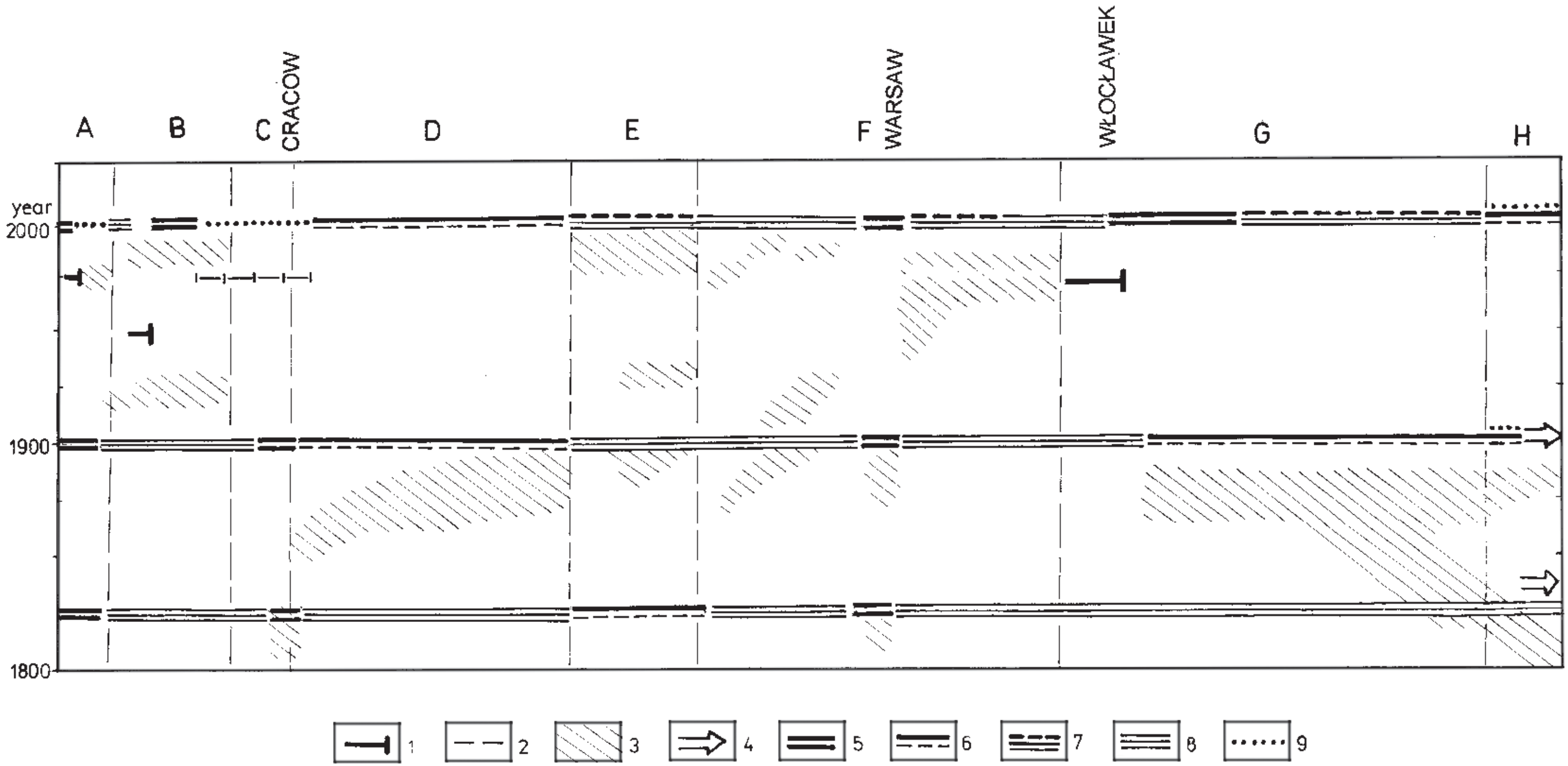


Figure 9. Channel regulation, embankments and erosional-depositional tendencies in the longitudinal profile of Vistula River during last two centuries. 1—water reservoirs (time of construction), 2—water steps and weirs, 3—main periods of channel regulation and construction of dam, 4—new outlets of Vistula River to the Baltic Sea, 5–9—main trends of fluvial processes in three time transects: before flood series in 1840s at the beginning and at the end of 20th century; 5—distinct tendency to downcutting, 6—downcutting prevailing over aggradation, 7—aggradation prevailing over downcutting, 8—distinct tendency to aggradation, 9—river section transformed to canal.

Source: elaborated by L. Starkel

necessary, as will reconstruction of natural channel patterns and riverside plant communities. Extensive polders for temporary flood water storage will need to be built, especially if we consider the increase in flood frequency during the progressive climate change. All these tasks are foreseen, but may not reach the investment stage. Restoration of fluvial ecosystems through reduction of the input of sewage and industrial pollutants has to progress simultaneously.

When comparing the Vistula with those Western or central European rivers whose headwaters are located in mountains (examples might be the Rhine, Elbe, Oder, or Danube (Petts *et al.* 1989), we can conclude that Vistula never attained any uniform system of channel regulation. The river still bears the 19-century traces of the different models of water management applied independently by each of the three countries then occupying partitioned Polish territory. For each of these countries, the Vistula played only the a marginal role of a frontier river.

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Paper first received: July 2006
In final form: July 2007

BOOK REVIEW

Hungarian Spaces and Places: Patterns of Transition, edited by G. Barta, É.G. Fekete, I. Kukorelli-Szörényiné, J. Timár, Centre for Regional Studies Hungarian Academy of Sciences, Pécs, Hungrary, 2005, 595 pp.—Dariusz Świątek

No more then five years ago the 10th anniversary of the transition in central and eastern Europe (CEE) was widely discussed (Lavigne, 2000), yet the 15th anniversary went almost unnoticed, without a large number of conferences, special issues of journals, reports, books, etc. However it did not past completely unnoticed, now over 15 years since the beginning of the transition from state socialism to capitalism, some researchers are arguing that this process is nearing the end, and some even announced its end. The group of Hungarian geographers re-assessed 15 years of changes in Hungary in book *Hungarian Spaces and Places Patterns of Transition*.

The book contains five parts which are created from 33 papers, preceded by a short but very useful introduction on transition issues in Hungary. Each paper makes one chapter which gives the impression that the whole book is rather a compilation than a coherent study. Having 33 authors in one book means it is difficult to shape it differently. To do justice it should be mentioned that the four editors made every effort to arrange the book in the way that makes it easier to move through the complex problems identified by the different authors. Apart from two parts on the direct and indirect impacts of political, economic and social transition, the book contains three parts on new patterns of spaces, places and uneven development in Hungary. The analyses of these changes show the effects of transition in different contexts, places and spaces.

At the beginning the study deals with regionalisation, an important contemporary Hungarian issue. As majority of authors from the first part of the book suggest, regionalisation is an inevitable process, not only because of Hungarian presence in international structures like EU or NATO, and globalization or modernization influences, but mainly because of national economic growth. A number of questions arise, such as whether new regional structures should be connected to public administration, how resources should be redistributed among the regions or how to reduce governmental control. These questions are answered in different ways in the first part of the book, dependent on the authors' views. However what seems to unite almost all of papers is belief that special attention should be paid to settlements and regions which are not integrated into the network regions. From all the chapters in this part of the book, we can draw the conclusion, expressed in one of the chapters, that regionalisation still needs long-term purposeful preparation.

The processes that have changed Hungarian economy since the beginning of the nineties re-made also spatial perspectives; new differences and inequalities appear in different areas and places of public life. The second part of the book *Spatial Processes in the Economy in the Era of Transformation* presents a number of empirical studies which deal with major sectors of economy like: agriculture, industry, service and retail. The main conclusion that arises from almost all these chapters is that Hungary is experiencing significant and increasing polarisation of economic space. This division is created by Budapest and adjacent regions on one hand, where the majority of industrial investments, financial services or ICT (Information and Communication Technologies) sector are located and on the other hand by rest of the country experiencing considerably lower economic activity.

Transformation also influenced the shape of Hungarian social space. New problems appear and others which were very often were hushed up during communism now become more visible. One of the most noticeable and probably unwanted results of changes was creation of unevenness which leads to such phenomena like poverty, social exclusion or segregation. Social problems exemplified in the book were oscillating around work, gender inequalities, and ethnic problems. All were depicted in the chapters grouped in the third (*Social trends in transition*) and fourth (*Changing places and spaces*) parts of the book. One of the most interesting examples shown here was the emergence of non-governmental organisations (NGOs). The analysis of this phenomenon in the context of Hungarian public life brings also questions about the consolidation of the democratic regime in Hungary. Unfortunately none of book's chapters is devoted to the policy issues which seem to be essential in the context of shaping both social and economic reality.

According its title, *Changing places and spaces*, the fourth part of the book seems to be the core of the volume. This part begins with an analysis of employment in Hungary (both rural and urban areas) and goes further to illustrating changes of Hungarian urban network in context of access to good and services, location of knowledge based investments, innovations and globalisation processes. Once again we can observe strong polarisation but this time of Hungarian urban space, with Budapest and regional centres on one side and the rest of the towns on the other. This impression of polarisation is underlined by two chapters that focus on cultural investments and architectural changes caused by new global trends in Budapest. All the chapters in this part contrast with the two last chapters not only because they describe transition of rural space and small villages, but also because these chapters include lists of suggestions for rural policy-makers which should lead to economic activation in this areas.

Euroregions and cross-border cooperation are the main topic of the last part of the book. All the chapters that deal with these issues include an extended historical background. After the First World War, the country was deprived of 2/3 of its territory and about 30% of its inhabitants (Kocsis 1998) and this fact in essential factor in shaping local cross-border cooperation, which seems to be very important in context of European integration. The last two chapters of this part raise problems of protection areas located along country borders giving good examples of good cooperation from Hungarian borders.

Besides the aforementioned lack of analysis of political changes, a picture of the changes in other areas of public life like education, health care or administration is also missing. However readers will find interesting in-depth analyses of changes that take place in Hungarian 'places and spaces' between 1990 and 2005. The majority of the book has an empirical character, which helps the reader to understand the nature of changes that took place in Hungary within last 15 years. The book can be recommended not only to readers interested in Hungarian changes but also to those interested in broad transformation processes.

Five years ago Hungarian economist Janos Kornai stated that although economic transformation in Hungary was not over yet, transition certainly was. The system had become capitalist. What was missing from a successful transformation was a set of broadly- understood institutions that would shape contemporary Hungarian space (Kornai 2000). Five year later after reading *Hungarian Spaces and Places Patterns of Transition* we can boldly abide by this statement.

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